Event detection capabilities of IEEE 802.15.4 Multi-Sink Wireless Sensor Networks

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Abstract— **Multi-sink wireless sensor networks are recently gaining interest. They have been introduced to overcome the scalability problem arising in single sink network architectures: by increasing the number of sensor nodes, the information collected at a single sink might become excessive with respect to its communication capacity. In this paper, the topologies formed by means of the IEEE 802.15.4 *association procedure*, i.e., *trees* rooted at sink nodes, are analyzed in terms of event detection capabilities. Specific attention is dedicated to the characterization of network lifetime and event notification reliability for different sinks distribution and varying the range of the event detection. Multi-sink topology performance are compared with classic single sink topology.**

I. INTRODUCTION

Wireless Sensor Networks (WSNs) are traditionally composed of devices (in the following named also nodes) distributed over a monitored region, which generate samples of a given phenomenon (e.g. atmospheric pressure, or temperature measurements) and forward them to a sink that collects the information possibly through a multi-hop wireless network [1], [2]. Recently, interest is emerging towards scenarios with multiple sinks, where nodes must form efficient data gathering trees and select the best sink to send these data [3], [4].

This rising interest is motivated, in the first instance, by scalability problems of single-sink network architectures. In fact, by increasing the number of sensor nodes, the information collected at the sink might become excessive with respect to its communication capacity. Moreover, the average number of hops between any source of data and the sink might overcome the radio channel capacity close to the sink (i.e., the region where all the generated samples must be gathered). Multi-sink networks can remarkably reduce the mean distance between nodes and sink, basically resulting in energy saving and longer lifetime.

In a multi-sink network, the sinks act as gateways forwarding sensed data towards the storage systems network e.g., the Internet. Each sink collects data generated only by a subset of devices and the overall monitored phenomenon is reconstructed at the data storage system. We remark that, even if having more sinks could enhance some network performance, a tradeoff exists. In fact, sinks usually consume considerable energy. Furthermore, they are connected to a data storage network by means of wired or wireless transport technologies (different from those used by the sensor nodes), and the increasing the number of sinks in a WSN can be unfeasible or it can considerably increase the network deployment costs.

This paper specifically focuses on IEEE 802.15.4 multi-sink WSNs. The IEEE 802.15.4 is an emerging air interface standard that represents an enabling technology for WSNs [5]-[9], and, as such, it attracts the interests of many researchers. In particular, the IEEE 802.15.4 defines the physical and MAC (Medium Access Control) layers, it includes a topology formation strategy based on a MAC *association procedure* (which will be described in the following), while leaving the choice of the routing and network formation criteria to the network designers and chipset manufactureres. Upper layers of the protocol stack are standardized by the ZigBee Alliance, which also deals with marketing and interoperability of WPAN (Wireless Personal Area Networks) devices from different manufacturers [7].
Few papers have been issued so far concerning IEEE 802.15.4 topology formation analysis or optimization [10], [11]. In particular, to the Authors' knowledge, papers dealing with multi-sink scenarios have not been issued yet.

In this paper, multi-sink topologies formed employing the IEEE 802.15.4 association procedure are analyzed in details. In particular, by means of the 802.15.4 module for Network Simulator [12], we collected several *forests* of disjoint trees resulting from the association procedure: since each tree corresponds to (and it is rooted at) one sink, and every node joins only one tree, the overall network topology in case of multi-sink scenario is better described as a forest of disjoint trees. To each forest, several performance metrics are associated to, e.g., the average energy consumed to reveal an event, the event detection reliability, etc.

The paper is organized as follows. Section II briefly describes the association procedure defined in the IEEE 802.15.4 to form a connected network. The considered network scenarios and simulation models are described in Section III. Sections IV is dedicated to discuss the results of the performance analysis. Finally main conclusions are drawn in Section V.

II. IEEE 802.15.4 TOPOLOGY FORMATION

An IEEE 802.15.4 WPAN [6] is composed of one PAN coordinator and a set of devices. The PAN coordinator is the primary controller of the network and it is responsible for initiating the network operations. The standard defines a set of procedures implemented by the PAN coordinator to initiate a new WPAN and by other devices to join a WPAN. The PAN coordinator assigns a PAN_ID (PAN identifier) to the network and selects a channel among those specified in the standard. The channel selection is performed by the Energy Detection

(ED) scan by means of which the measure of the *peak energy* in each channel is returned. This *peak energy* is the maximum energy measured on the channel and gives indications on the interference present on that channel.

The procedure adopted by devices to join a WPAN is named *association procedure* and it establishes relationships between devices within a WPAN. The operations performed by a device to join a WPAN are: 1) the device searches for all the available WPANs, 2) it selects a WPAN according to predefined criteria and 3) starts the message exchange with the selected WPAN, contacting the nearest coordinator belonging to the chosen WPAN[1].

The discovery of available WPANs (step 1) is performed by scanning the *beacon frames* broadcasted by the coordinators. Two beacon broadcasting modes are defined in the standard: beacon-enabled and nonbeacon-enabled.

In beacon-enabled mode, the associated devices transmit beacon frames periodically, hence the information on the available WPANs can be derived by eavesdropping the wireless channels (passive scan). In nonbeacon-enabled mode, the beacon frames shall be explicitly requested by a device by means of a *beacon request command frame* (active scan).

In the beacon-enabled mode, the time is divided into a superframe structure. The superframe is bounded by beacon frames that are transmitted periodically and that allow nodes to synchronize. The active part of the superframe is divided into 16 contiguous time slots that can be configured in three different modes: beacon time slot, Contention Access Period slots and Contention-Free Period slots. At the end of each superframe an inactive period can be activated for power saving purposes.

After the channels scanning the device selects the network it want to connect to (step 2), and (step 3) it sends an *association request* message to the coordinator. The coordinator grants and denies the access to the network of the new device by replying with an *association response command frame*. It is important to notice that the association criteria, performed at step 2, are not defined in the standard but are implementor dependent.

The whole association procedure results in a set of *parent-child* relationships between devices. These relationships define univocally a tree rooted at the PAN coordinator.

III. NETWORK SIMULATION SCENARIOS

To create a large set of tree-based topology realizations using the IEEE 802.15.4-compliant topology formation procedures, we extended the *ns-2* module (originally provided by Zheng in [12]) to simulate IEEE 802.15.4 multi-sink networks.

Since no specific channel and coordinator selection algorithms have been defined in the standard, we implemented two simple mechanisms based on the perceived link quality. In particular, the PAN coordinator chooses the channel for the WPAN on the basis of the measured interference as follows:

- if the *peak energy* of all channels is above the maximum detectable energy level threshold (high interference channels), the channel is randomly selected;
- if the *peak energy* of all channels is bounded between the maximum and the minimum detectable thresholds, the lowest energy channel is selected;
- if the *peak energy* of one or more channels is equal to the minimum threshold (low interference channels), the channel is randomly selected among these channels.

Similarly, the nodes randomly select the coordinator, i.e., the WPAN to join, among those for which the measured link quality is bounded between the maximum received energy and γ times this value (with $\gamma = 0.8$). These simple algorithms prevent biases to emerge during the channel/coordinator selection phase.

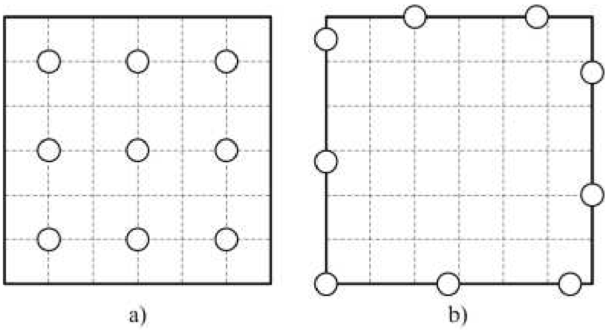

Fig. 1. Network simulation scenarios.

Figure 1 depicts the two bi-dimensional multi-sinks deployment patterns we considered in simulations:

- *Scenario 1*: the sinks are placed on a squared grid; due to this sinks disposal and to the selected transmission range, the sinks cover the whole area.
- *Scenario 2*: the sinks are equally distributed along the perimeter of the square; in this case they do not cover completely the monitored field.

Both scenarios model real WSN applications. Scenario 1 represents a classical bi-dimensional grid deployment, while Scenarios 2 is considered in order to account application scenarios where sinks can not be installed within the monitored region, e.g., forests, lakes, etc.

In each simulation, we randomly place $N = 500$ nodes within the square region of side $L = 1000m$ and area A. We considered two different number of sinks S in simulations: $S = 9$ and $S = 49$. Moreover, in order to compare the simulation results with the single sink case, we carried simulations also with $S = 1$. As for the single sink case, in the Scenario 1 the sink is located on the center of the area where the nodes are spaced, while in the Scenario 2 the sink is located in the center of one side of the area.

All sensor nodes are configured to act as possible coordinators in each WPAN. Moreover, every sink is configured in beacon-enabled-mode and the inactive part of the superframe is absent. All other nodes operate in nonbeacon-enabled mode. As for the propagation model, the *two-ray ground reflection model* [13] is used; the model contemplates both the direct path and one ground reflection path. The transmission range of both sinks and sensor nodes is fixed to 150 meters.

In order to compare the same number of IEEE 802.15.4 association trees T, for each analyzed scenario we carried out

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[1] Coordinators are sinks or those nodes that can act as relay nodes.

M independent simulation runs, with $M = T/S$ and $T = 10000$.

Since we are interested in the network lifetime, event detection reliability and overall energy consumption, we associate to each topology generated by means of ns-2 simulator, random generated events to each of the M forest, varying the range of the event e_r (i.e., the number of neighbor nodes that detect the event). In particular, given a ns-2 generated forest, random events (of a fixed event range) are generated till the dead of the sensor network. At the dead of the network, the number of measured events (that is a measure of the forest lifetime), the node which caused the death of the whole forest, its level (node at level $i = 0$ indicate the sinks, $i = 1$ the nodes directly connected to the sinks, $i = 2$ the nodes whose parents are 1-nodes, etc.) and the average number of sinks every event is notified to, are recorded. This operation is repeated 100 times for each forest and for each event range.

We assume that the network dies when, given the current monitored event, all the sinks, belonging to trees where the event is detected, are unreachable, that is for each of the e_r paths from the nodes which detected the event to their relative sinks, at least one node on the path consumed all the energy.

The generation of the events and the way the event is reported to the sinks is done under the following assumptions:

- Routing protocols - The routing between the sender and the destination is defined by the position of the nodes in the tree, i.e. the IEEE 802.15.4 association procedure always defines the hierarchical routing path.
- Ideal data aggregation - An event detected from two or more sensors belonging to the same tree generates a single event notification to the sink.
- Event range and traffic generation - An event is generated randomly in a small area and the event range e_r indicates the number of nodes that detect the event. At the event detection, every involved node generates a packet directed to the sink of the WPAN it belongs to (packets generated in the same tree are then aggregated ideally as previously indicated).
- Energy consumption - Both transmission and reception of a packet consume a constant amount of energy E_0 independently of the distance between the sender and the receiver (no power control). At the beginning of the simulation every node (apart the sinks that never die) has a fixed amount of energy equal to 100 times E_0. Data aggregation does not consume energy and the sleep mode is disabled.
- Collisions - As far as regards the MAC layer we assume that the wireless channel is collision free (i.e., collisions are negligible) and that a packet is always received successfully to receivers within the fixed transmission range of the sender.

In Table I simulation assumptions and parameters are summarized.

For each of the ns-2 simulation scenarios we associated the following metrics:

- normalized mean number of detected events before the death of the forest;
- mean level in the tree of the node which has caused the death of the forest;
- mean number of sinks which detect the event at the same time;
- percentage of energy consumption per event in the forest.

TABLE I

SIMULATION ASSUMPTIONS AND PARAMETERS

Parameter	Value
Routing	Hierarchical
Data aggregation	Ideal
Event range e_r	from 1 to 10
Traffic	1 packet for each event
Transmission energy E_{TX}	Constant value E_0
Reception energy E_{RX}	Constant value E_0
Initial Energy of the sensor nodes	$100 * E_0$
Consumption for data aggregation	Negligible
Power Control	Disabled
Sleep Mode	Disabled
Collisions	Negligible

In Algorithm 1, we report the pseudocode of the operations which are executed in order to determine the above metrics. The nodes in the network are indicated as $x^{(k)}$ and their energy value as $E_{x^{(k)}}$, with $k = 0, 1, ..., N-1$.

Algorithm 1 METRICS EVALUATION

```
for each forest do
  for event range $e_r = 1$ to $10$ do
    for number of runs $= 1$ to $100$ do
      /* set the initial energy of the sensor nodes */
      $\forall x^{(k)}, 0 \leq k \leq N-1, E_{x^{(k)}} = 100 * E_0$;
      $ForestIsAlive = TRUE$;
      while $ForestIsAlive$ do
        select a random node $x^{(0)}$;
        calculate and store the path $r_0$ from $x^{(0)}$ to the respective PAN coordinator/sink;
        /* find the $e_r - 1$ neighbors of $x^{(0)}$ */
        for $j = 1$ to $e_r - 1$ do
          find the node $x^{(j)}$: $d^e_{x^{(0)}x^{(j)}} < d^e_{x^{(0)}x^{(k)}}$, $j+1 \leq k \leq N-1$;
          calculate and store the path $r_j$ from $x^{(j)}$ to the respective PAN coordinator/sink;
        end for
        $unusablePaths = 0$;
        for $j = 0$ to $e_r - 1$ do
          decrease the energy $E_{x^{(k)}}$ of the nodes $x^{(k)}$ belonging to path $r_j$, for data packet delivery to the sink;
          /* energy decreased for each transmission and reception, considering data aggregation */
          if $\exists x^{(k)} \in r_j$: $E_{x^{(k)}} < 0$ then
            $unusablePaths++$;
          end if
        end for
        if $unusablePaths$ is equal to $e_r$ then
          $ForestIsAlive = FALSE$;
        else
          increase the number of detected events;
          update the sinks which detected the event;
        end if
      end while
      calculate and store the interesting metrics;
    end for
  end for
end for
```

In particular, it is shown how the e_r nodes which detect the event are found; i.e., initially a node $x^{(0)}$ that generates the event is extracted randomly; then, all the other nodes $x^{(k)}$ are ordered according to the Euclidean distance $d^e_{x^{(0)}x^{(k)}}$ from $x^{(0)}$ and the $e_r - 1$ closest nodes are selected. From line 7 to line 29 of the Algorithm 1, the death of the forest is computed: i.e., when, for each of the e_r paths from the e_r selected nodes to their respective sinks, it exists at least one node $x^{(k)}$ out of energy ($E_{x^{(k)}} < 0$). We remark that the amount of energy consumed by the nodes involved in the event data delivery, decreases (as shown at line 17 of the Algorithm 1) according to the ideal data aggregation assumption: every node, parent of two or more nodes that notify the event, sends only one data packet towards the sink. This models the fact that the node waits for possible notifications from its descendants before sending the packet to the sink.

IV. SIMULATION RESULTS

In this section, we analyze the effect of multi-sinks on the performance of the sensor network. We are interested in the network lifetime, event detection reliability and overall energy consumption.

Figure 2 depicts the normalized mean number of detected events before the death of the forest, for each considered scenario. The number of detected events is normalized with respect to the initial energy. As it is possible to notice, for all scenarios the normalized mean number of detected events decreases as the event range increases. When e_r increases, in fact, more energy is consumed for each event due to the following reasons:

- separate paths (e_r paths) between source nodes and sinks are present increasing the consumed energy per event;
- the distance between the furthest node among the e_r that detect the event and the relative sink increases.

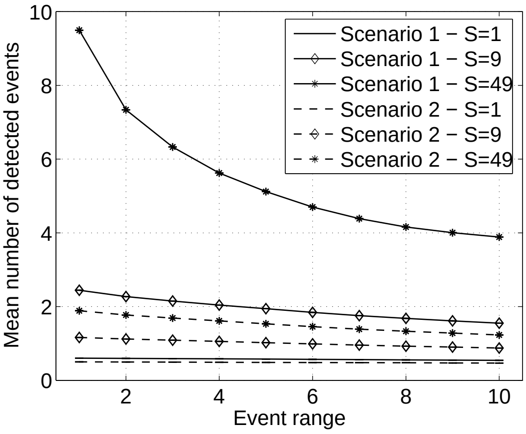

Fig. 2. Normalized mean number of detected events before the death of the forest.

By fixing the event range, the number of detected events increases when the number of sinks increases. It has to be pointed out that, in general, the nodes that waste the highest amount of energy are the ones around the sinks; employing more sinks, the wasted energy is better distributed among several nodes and the network lifetime grows up. Furthermore, increasing the number of sinks increases the reliability of the event detection: Figure 3 depicts the mean number of sinks a given event is reported to. The mean number of sinks that receives the event notification report increases with e_r because the higher is e_r, the more likely the source nodes belong to different trees. This effect is more noticeable when the number of sinks S grows up, because the number of trees which form the forest increases and of consequence, the number of trees involved in the event detection increases.

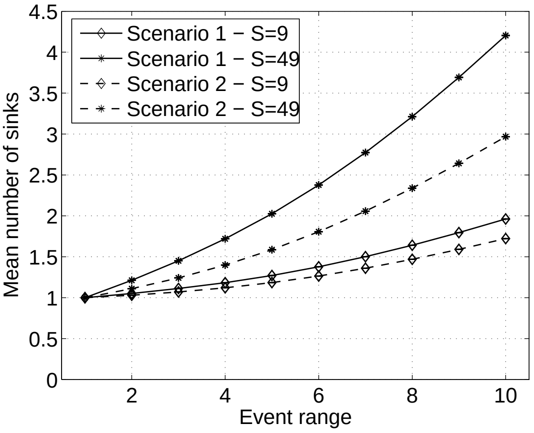

Fig. 3. Mean number of sinks which detect the event at the same time.

In Figure 4, the mean level of the node which has caused the death of the forest is reported for all the considered scenarios. The mean level of the node which caused the death of the forest increases with e_r. For low value of e_r this node is next to the sink (at 1st or 2nd level) because the effect of the ideal data aggregation is absent (e_r = 1) or negligible. In this case nodes close to the sink run out of energy earlier, because they are involved in more event notification delivery towards the sink. On the other hand, the mean level increases a little (e.g., 3 or 4) when e_r increases because, since it is likely that more source nodes are in the same tree (the same WPAN), nodes which aggregate data are placed at higher level (nearer to the leaves)

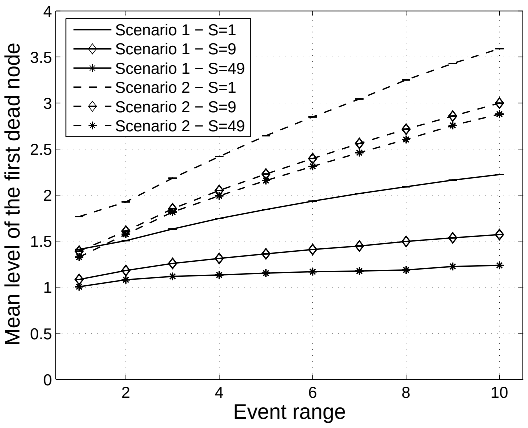

Fig. 4. Mean level of the node which has caused the death of the forest.

and they consume more energy. It is to point out that this effect is mitigated in multi-sink topologies and is not highly affected by the number of employed sinks.

Figure 5 depicts the percentage of energy consumed per event. The global energy consumption decreases with the number of sinks. This depends on the fact that, by increasing S, the trees heights decrease. Moreover, as the number of sinks increases, for a given event range, there are more WPANs able to detect the event and the energy consumption is more distributed with respect to the case of a reduced number of sinks.

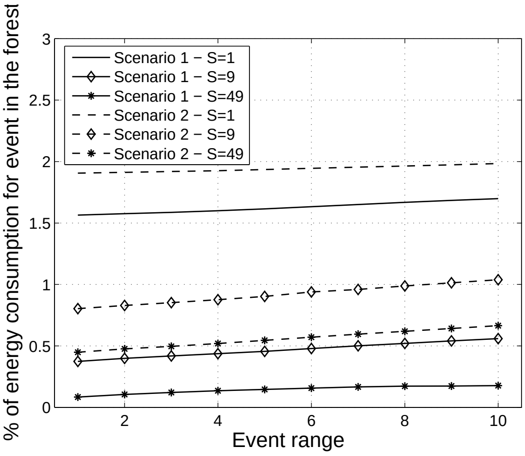

Fig. 5. Percentage of energy consumption per event in the forest.

On the other hand, when the event range increases the energy consumption per event increases too. It depends on the number of nodes involved in the event measurement and forwarding (multiple paths towards the sinks), and on the specific data aggregation model adopted.

As it is possible to note, fixed the number of sinks, performance obtained with Scenario 1 sink deployment are better than the one in Scenario 2. That is due to the shape of the trees formed during the WPAN set-up: in Scenario 1, trees are wider at lower level then in Scenario 2, i.e., shorter paths towards the sinks are present in Scenario 1.

In general, multi-sinks topologies provide better performance with respect to single sink topologies. Multi-sinks guarantee a higher network lifetime and a higher redundancy with respect to the information to be sent towards the sinks. However, the adoption of a multi-sink scenario implies higher costs for the installation and maintenance of the sinks. It is to point out that the increased costs are not always proportional to the performance gain and often the performance gain depends on the application scenario. For instance, increasing the number of the sinks S in Figure 3, redundancy detection level does not increase proportionally. Therefore, the choice of the scenario to be used depends on the requirements of the specific application and on the costs to be supported to achieve the desired performance.

It is worth to pinpoint that previous analysis and conclusions have been carried out assuming a uniform distribution in the event generation and cannot be generalized to different distributions.

V. OVERALL RESULTS AND CONCLUSIONS

IEEE 802.15.4 multi-sink wireless sensor networks are considered in this work, since several realistic application scenarios are currently addressing multi-sink network deployment to overcome the scalability problem imposed by the single sink topologies. Specific attention is dedicated to the analysis of multi-sink topologies formed by means of the IEEE 802.15.4 association procedure. Routing paths from sensors to sinks coincide with the association tree created during the network formation.

The benefits of deploying multi-sink wireless sensor networks in terms of network lifetime and event reporting reliability are analyzed in the paper under the assumption that events are generated randomly with a uniform distribution. Simulation results show that multi-sinks network deployment provides better performance with respect to single sink topologies. Multi-sinks guarantee higher network lifetime and a higher redundancy with respect to the information to be sent towards the sinks. However, the adoption of a multi-sink scenario implies higher costs for the installation and maintenance of the sinks. It is to point out that the increased costs are not always proportional to the performance gain and often the performance gain depends on the application scenario.

ACKNOWLEDGMENT

This work has been partially supported by the EC-funded Network of Excellence CRUISE, in the framework of the FP6.

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